

Discovery of blue companions to two southern Cepheids: WW Car and FN Vel

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ABSTRACT

A large number of high-dispersion spectra of classical Cepheids were obtained in the region of the Ca II H+K spectral lines. The analysis of these spectra allowed us to detect the presence of a strong Balmer line, H ϵ , for several Cepheids, interpreted as the signature of a blue companion: the presence of a sufficiently bright blue companion to the Cepheid results in a discernible strengthening of the Ca II H + H ϵ line relative to the Ca II K line. We investigated 103 Cepheids, including those with known hot companions (B5–B6 main-sequence stars) in order to test the method. We could confirm the presence of a companion to WW Car and FN Vel (the existence of the former was only suspected before) and we found that these companions are blue hot stars. The method remains efficient when the orbital velocity changes in a binary system cannot be revealed and other methods of binarity detection are not efficient.

Key words: stars: binaries: spectroscopic – stars: variables: Cepheids – stars: individual: WW Carinae – stars: individual: FN Velorum

1 INTRODUCTION

Classical Cepheids are radially pulsating F–G supergiants. Their regular variability makes them ideal standard candles in establishing the cosmic distance scale via the period–luminosity (P – L) relationship. The calibration of this relationship has a century-long history, and there is still need for improving the zero-point (Freedman & Madore 2010).

Cepheids which are members of binary systems can be suitable calibrators only if the luminosity of the Cepheid component can be disentangled from the luminosity of the companion star: if the companion remains unrevealed, its photometric effect can falsify the luminosity determination of the Cepheid. Because the incidence of binaries exceeds 50 per cent among classical Cepheids (Szabados 2003a), studying the binarity of individual Cepheids is an important task which is impeded by the fact that the companions are usually much fainter than the supergiant Cepheids.

Companions to Cepheids can be discovered by all conventional methods used for revealing binarity involving spectroscopy, photometry, and astrometry. There are some specific photometric methods only applicable for Cepheids summarized by Szabados (2003b).

Because most of the detectable companions are early type main-sequence (or slightly more evolved) stars whose flux dominates the ultraviolet part of the binary spectrum, UV spectroscopy with the *IUE* satellite was especially successful in disclosing the binarity of Cepheids (Evans 1992). In the absence of UV spectra, there is a complementary method based on a specific portion of the optical spectrum for detecting blue secondary stars efficiently.

This method, referred to as the calcium-line method, is based on the spectrophotometry of the 3900–4000 Å part of the visible region. This interval covers the Ca II H (3968.47 Å) and the Ca II K (3933.68 Å) lines as well as the H ϵ (3970.07 Å) line of the hydrogen Balmer series. The Ca II H and K lines in spectra of normal Cepheids without bright companions have practically equal depths (or residual flux). (We refer to the line profiles of Cepheids not accounting for narrow overlapping interstellar lines). If, however, a hot companion is present, the H ϵ line from the secondary star is superimposed on the Ca II H line and the resulting blend of these two lines is deeper than the Ca II K line (see Fig. 1). This technique of ‘intensity reversal’ was first used by Miller & Preston (1964a; 1964b) for Cepheids. Later on, Evans (1985) showed that this method can be applied for detecting companions hotter than A3V spectral type stars.

In the last three decades this method was neglected. In

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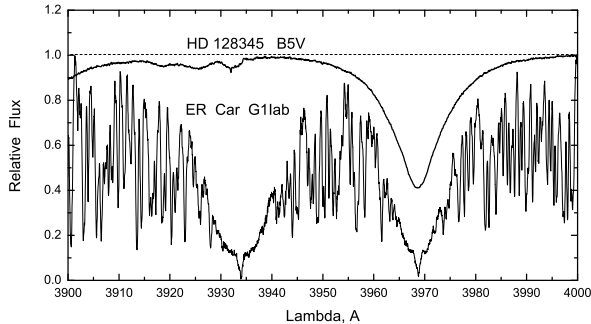


Figure 1. Spectra in the region of the strong Ca II H + K spectral lines: a typical Cepheid without bright companion (lower spectrum); a main-sequence B-star (upper spectrum). The narrow absorption features near the line cores are of interstellar origin.

view of the fact that there is no dedicated space mission for obtaining UV spectra, we decided to perform an optical spectroscopic survey of a large number of Cepheids to reveal hot companions, i.e. new binaries.

2 OBSERVATIONS

The region of the Ca II H + K lines was studied in the spectra of all 103 Cepheids listed in the paper by Luck et al. (2011). The list of the target Cepheids is given in their Table 1.

High signal-to-noise spectra were obtained in the period 25 March – 1 April 2010 using the 2.2 m MPG telescope and FEROS spectrograph at ESO La Silla. The spectra cover a continuous wavelength range from 3800 to 8700 Å with a resolving power of about 48000. Typical maximum signal-to-noise (S/N) values (per pixel) for the spectra are in excess of 150. Each night we observed a broad-lined B star with a S/N exceeding that of the programme stars to enable cancellation of telluric lines where necessary.

We used IRAF to perform CCD processing, scattered light subtraction, and echelle order extraction. For these spectra two extractions were done, one uses a zero-order (i.e., the mean) normalization of the flat field which removes the blaze from the extracted spectra. The second one uses a high-order polynomial to normalize the flat-field which leaves the blaze function in the extracted spectrum. The latter spectrum reflects more accurately the true counts along the orders. A Windows based graphical package (ASP) developed by R. Earle Luck was used to process the blaze removed spectra. This included Beer’s law removal of telluric lines, smoothing with a fast Fourier transform procedure, continuum normalization, and wavelength calibration using template spectra. Echelle orders show significant S/N variations from edge to maximum due to blaze efficiency. To maximize the S/N in these spectra we have co-added the order overlap region using as weights the counts from the second data extraction. The co-added spectra were then inspected and the continua sometimes modified by minor amounts in the overlap regions.

Anomalous profiles of the Ca II H + K lines, indicative of the presence of a hot companion, were found only in ten of these spectra. The data on these Cepheids are listed in Table 1. The spectra of Cepheids were obtained predominantly

Table 1. Cepheids with anomalous profiles of the Ca II H + K lines

Cepheid	P (d)	$\langle V \rangle$	Sp(Cep)	R_{KH}	Sp(comp)
<i>known binaries:</i>					
KN Cen	34.0296	9.87	G8Iab	2.09	B6.0 V
V659 Cen	5.6218	6.60	F6/F7Ib	1.61	B6.0 V
AX Cir	5.2733	5.88	F8II	1.67	B6.0 V
BP Cir	2.3984	7.56	F2/F3II	1.27	B6.0 V
V1334 Cyg	3.3330	5.87	F1II	1.86	B7.0 V
S Mus	9.6599	6.12	F6Ib	1.44	B3.5 V
SY Nor	12.6457	9.51	F9Ib	1.92	B4.5 V
V636 Sco	6.7968	6.65	F7/F8Ib/II	1.29	B9.5 V
<i>new binaries:</i>					
WW Car	4.6768	9.75	F9II	1.35	?
FN Vel	5.3242	10.29	F9II	1.42	?

at maximum brightness, in order to reach the highest S/N and to perform a full abundance analysis (Luck et al. 2011). However, the optimal way to search for companions is to use spectra of Cepheids at minimum brightness when the contribution of possible companions to the spectra of the target Cepheid is the highest. Therefore we cannot exclude that a few hot companions remain unnoticed. In the case of known binary Cepheids, not all spectra show anomalous behaviour of the Ca II H + K lines, either because the companion is too faint, or it is of late spectral type.

3 EFFECT OF A BLUE COMPANION ON THE Ca II H + K LINES

3.1 Cepheids with known blue companion

Cepheids with known blue companions have been selected from the list of Galactic Cepheids in binary systems (<http://www.konkoly.hu/CEP/nagytab3.html>). These target Cepheids are listed in the upper section of Table 1 whose subsequent columns give the name of the Cepheid, the pulsation period (in days), the mean V brightness, the spectral type of the Cepheid, the ratio of the residual fluxes defined below, and the spectral type of the blue companion. The relevant part of the observed spectra is shown in Fig. 2. It is clearly seen that the blend of the Ca II H and H ϵ lines is stronger than the Ca II K line.

To test the presence of a possible hot companion, we used the ratio of residual fluxes, $R_{KH} = r_{\lambda}(K)/r_{\lambda}(H)$. A typical value of the ratio for Cepheids without hot companions is $R_{KH} = 1.00 \pm 0.03$. As expected, the ratios for the stars with known hot companions show larger values ranging from 1.29 to 2.09 (see Table 1).

3.2 Cepheids with newly revealed blue companion

A similar intensity reversal was searched for in the spectra of other Cepheids, and it was found that WW Car and FN Vel have a formerly unrevealed blue companion. Indeed, the $r_{\lambda}(K)/r_{\lambda}(H)$ ratio has a value of 1.35 in the case of WW Car and of 1.42 in the case of FN Vel, well above 1.00. The basic data on these two Cepheid variables are listed in Table 2 and their spectra near the Ca II H + K lines are

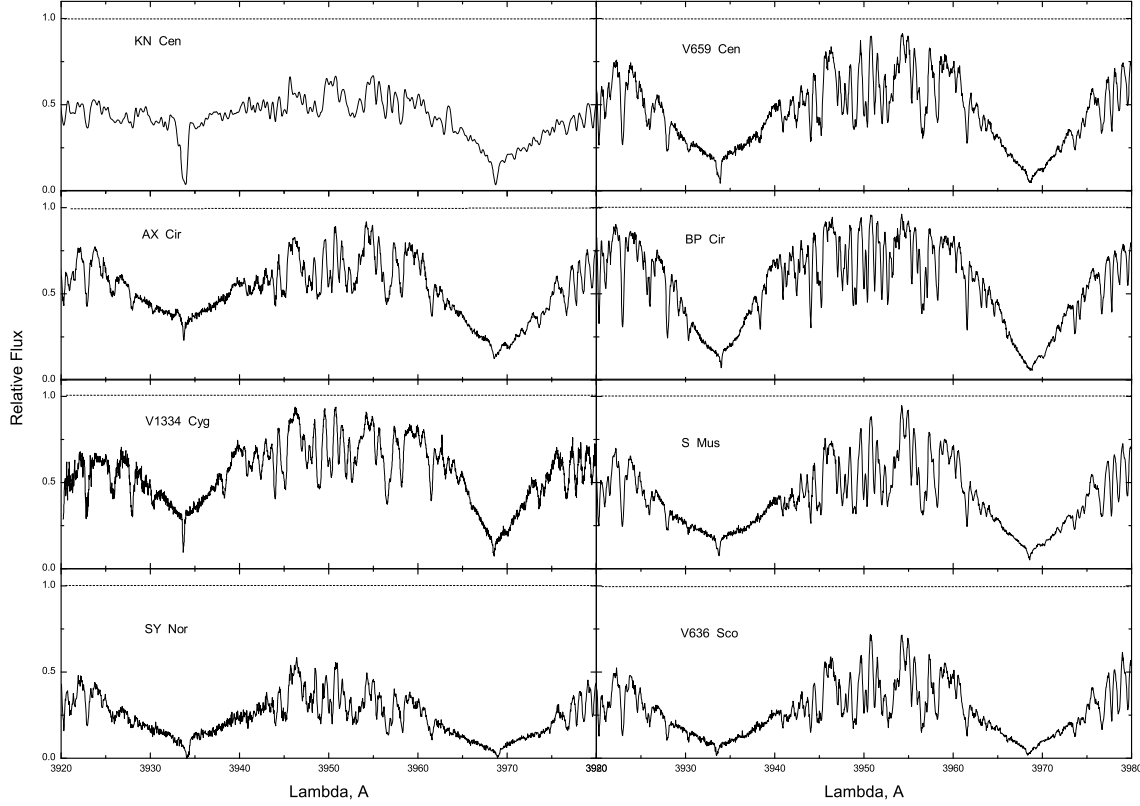


Figure 2. Spectra of 8 classical Cepheids with known B type companion in the region of the Ca II H+K lines.

Table 2. New binary Cepheids with blue companions. The accurate value of the pulsation period (col. 2) is from Sect. 4. The Julian Date of the spectral observation (col. 7) and the corresponding phase (col. 8) have been calculated from the newly determined ephemerides. The mean V brightness (col. 3) and $B - V$ colour index (col. 4) in the Johnson photometric system are from Berdnikov et al. (2000); the colour excess, $E(B - V)$ (col. 5) and the atmospheric iron content $[\text{Fe}/\text{H}]$ (col. 6) are both from Luck et al. (2011).

Cepheid	Period (day)	$\langle V \rangle$ (mag)	$\langle B - V \rangle$ (mag)	$E(B - V)$ (mag)	$[\text{Fe}/\text{H}]$	JD 2 400 000+	phase	Exp. (sec)	S/N
WW Car	4.676818	9.748	0.899	0.379	-0.07	55282.603	0.849	1200	218
FN Vel	5.324170	10.292	1.186	0.588	0.06	55283.591	0.224	2100	251

shown in Fig. 3.

4 DISCUSSION

All information on both WW Car and FN Vel available in the literature was collected for two main reasons, viz.:

- to find additional evidence of binarity;
- to determine the accurate value of the pulsation period in order to calculate the phase of the spectral observation.

The updated period was determined by the $O - C$ diagram method (Sterken 2005). The newly determined

ephemerides can be used when planning any future observations of these Cepheids.

All published photometric observations of WW Car and FN Vel were re-analysed in a homogeneous manner to determine seasonal moments of the chosen light curve feature. The relevant data listed in Tables 3 and 4, respectively, are as follows:

- Column 1: the heliocentric moment of the selected light curve feature (moment of maximum brightness);
- Col. 2: the epoch number, E , as calculated from equations (1) and (2), respectively:

$$C = 2\,453\,047.7725 + 4.676\,818 \times E \pm 0.0032 \pm 0.000\,002 \quad (1)$$

$$C = 2\,453\,775.6587 + 5.324\,170 \times E \quad (2)$$

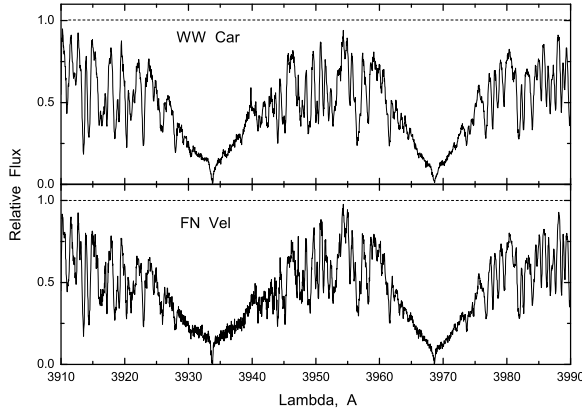


Figure 3. Spectra of two new binary classical Cepheids WW Car and FN Vel. It is noticeable, that the Ca II H + He line is enhanced relative to the Ca II K line.

$$\pm 0.0022 \pm 0.000\,005$$

(These ephemerides have been obtained by the weighted linear least squares fit to the $O - C$ differences for both Cepheids);

- Col. 3: the corresponding $O - C$ value;
- Col. 4: the weight assigned to the $O - C$ value (1, 2, or 3 depending on the quality of the light curve leading to the given difference);
- Col. 5: the source of the data.

4.1 WW Carinae

The variability of WW Carinae was discovered by Henrietta Leavitt (Pickering 1906). The period determined somewhat later by Arville Walker (Pickering 1912), $P = 4.676$ d, is correct but no type of variability was assigned to the star. Szeligowski (1926) published a series of photographic observations covering the years 1924–1926. In his paper, WW Car is already considered as a Cepheid. The available photoelectric and more recent CCD photometric data involve those by Walraven et al. (1958), Irwin (1961), Pel (1976), Pojmanski (2002), Berdnikov (2008), as well as the observations by the *Hipparcos* satellite (ESA 1997), and Optical Monitoring Camera (OMC) on board the *INTEGRAL* space probe. The most recent photometric data are accessible on the the AAVSO web page¹. From multi-colour photometry, Madore & Fernie (1980) suspected the existence of a blue companion to WW Car.

The moment of maximum brightness was determined for each data series from the annual phase curves. When constructing the $O - C$ diagram, the $O - C$ values for the moments of maximum brightness of WW Car have been obtained from the ephemeris 1, and are listed in Table 3. The $O - C$ diagram in Fig. 4 indicates long-term changes in the pulsation period. The wave-like nature of these variations could be due to the light-time effect in a binary system. The available five radial velocity data covering only a week of observations (Pont, Burki & Mayor 1994)

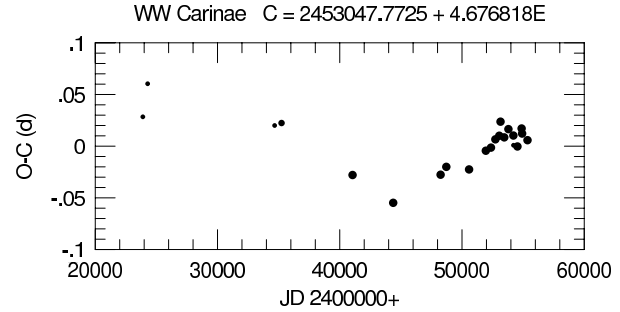


Figure 4. $O - C$ diagram for WW Car.

Table 3. $O - C$ values of WW Car (see the description in the text).

JD _⊙ 2 400 000 +	<i>E</i>	<i>O - C</i>	<i>W</i>	Data source
23891.5175	−6234	0.0284	1	Szeligowski (1926)
24285.4022	−6150	0.0604	1	Szeligowski (1926)
34672.5746	−3929	0.0200	1	Walraven et al. (1958)
35238.4720	−3808	0.0224	2	Irwin (1961)
41047.0296	−2566	−0.0279	3	Pel (1976)
44372.2203	−1855	−0.0548	3	Berdnikov (2008)
48249.3296	−1026	−0.0276	3	<i>Hipparcos</i> (ESA 1997)
48717.0190	−926	−0.0200	3	<i>Hipparcos</i> (ESA 1997)
50578.3901	−528	−0.0225	3	Berdnikov (2008)
51948.7159	−235	−0.0044	3	ASAS (Pojmanski 2002)
52369.6325	−145	−0.0014	3	ASAS (Pojmanski 2002)
52729.7555	−68	0.0066	3	ASAS (Pojmanski 2002)
53047.7826	0	0.0101	3	ASAS (Pojmanski 2002)
53150.6862	22	0.0237	3	<i>INTEGRAL</i> OMC
53454.6642	87	0.0085	3	ASAS (Pojmanski 2002)
53796.0799	160	0.0165	3	ASAS (Pojmanski 2002)
54202.9568	247	0.0103	3	ASAS (Pojmanski 2002)
54212.3011	249	0.0009	1	<i>INTEGRAL</i> OMC
54535.0003	318	−0.0003	3	ASAS (Pojmanski 2002)
54876.4254	391	0.0171	3	ASAS (Pojmanski 2002)
54918.5119	400	0.0122	3	<i>INTEGRAL</i> OMC
55358.1264	494	0.0058	3	AAVSO

are, however, insufficient to study this possibility. The short-term scatter of the data points in Fig. 4 reflects the observational error and uncertainties in the data analysis.

From a spectroscopic point of view, WW Car has been a neglected star. Even the F0 spectral type given by the SIMBAD database might be incorrect for a genuine Cepheid variable. In addition to the five radial velocity measurements obtained in 1983 (Pont, Burki & Mayor 1994), the atmospheric composition was studied by Luck et al. (2011), Luck & Lambert (2011), and Usenko et al. (2011).

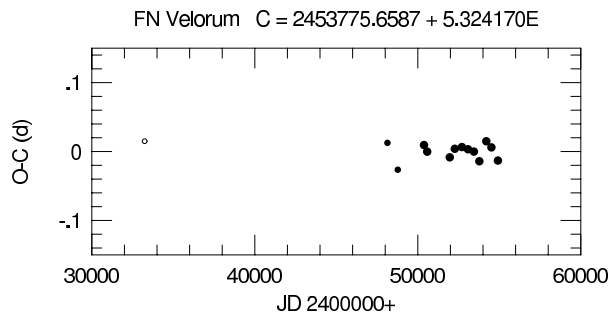
4.2 FN Velorum

The brightness variability of FN Velorum was revealed by O’Connell (1951). He already classified this variable as a Cepheid and published a correct period. Then this Cepheid had been neglected for decades. More recent photometric data are available from the *Hipparcos* mission (ESA 1997), the ASAS sky survey (Pojmanski 2002), and the

¹ <http://www.aavso.org/apps/webobs/results/?star=WW+CAR>

Table 4. $O - C$ values of FN Vel (see the description in the text).

JD_{\odot}	E	$O - C$	W	Data source
2 400 000 +				
33240.35	-3857	0.015	1	O’Connell (1951)
48137.3753	-1059	0.0126	2	<i>Hipparcos</i> (ESA 1997)
48770.9125	-940	-0.0264	2	<i>Hipparcos</i> (ESA 1997)
50378.8476	-638	0.0094	3	Berdnikov (2008)
50575.8323	-601	-0.0002	3	Berdnikov (2008)
51960.1083	-341	-0.0084	3	ASAS (Pojmanski 2002)
52268.9226	-283	0.0040	3	ASAS (Pojmanski 2002)
52705.5070	-201	0.0065	3	ASAS (Pojmanski 2002)
53078.1957	-131	0.0033	3	ASAS (Pojmanski 2002)
53440.2359	-63	-0.0001	3	ASAS (Pojmanski 2002)
53775.6446	0	-0.0141	3	ASAS (Pojmanski 2002)
54201.6072	80	0.0149	3	ASAS (Pojmanski 2002)
54515.7243	139	0.0060	3	ASAS (Pojmanski 2002)
54915.0180	214	-0.0131	3	ASAS (Pojmanski 2002)


Figure 5. $O - C$ diagram for FN Vel.

database containing Berdnikov’s photometric observations of Cepheids (Berdnikov 2008). The seasonal normal maxima listed in Table 4 have been determined from these data. The $O - C$ diagram is plotted in Fig. 5. The plot can be approximated by a constant period corresponding to the ephemeris 2 for the moments of the maximum brightness. The scatter of the points in Fig. 5 reflects the observational error and uncertainties in the analysis of the data.

Spectroscopic observations of FN Vel started only recently. Luck et al. (2011) studied the atmospheric chemical composition and determined $[Fe/H] = +0.06$. Moreover, Anderson (2013) revealed that FN Vel belongs to a spectroscopic binary system, and even the spectroscopic orbit could be successfully determined from his own extensive radial velocity measurement series. The orbital period of the binary system is 471.654 days. This spectroscopic binarity is a strong evidence of the reliability of the method for binarity detection applied in the present paper.

5 CONCLUSION

We used the so-called “calcium-line method” to investigate the presence of hot blue companions to 103 southern Cepheids. In this method, the strong Balmer line, $H\epsilon$, of the companion superimposes on the $Ca II H$ line of the Cepheid, resulting in the strengthening of the $Ca II H$ line with respect to the $Ca II K$ line in the compound spectrum of the

binary system. (The $Ca II H$ & K lines have practically equal depths in single Cepheids).

The method allowed us to recover eight Cepheids with known blue companions in our sample and led to the discovery of hot companions for two more Cepheids, WW Car and FN Vel. In the case of FN Vel, this is an independent confirmation of binarity published by Anderson (2013) in his PhD Thesis. WW Car has also been suspected in having a blue companion from photometry (Madore & Fernie 1980).

As Cepheids are used as standard candles in determining the cosmic distance scale, it is important to disentangle the luminosity of the Cepheids from that of their companion when calibrating the $P-L$ relationship. Therefore the binarity of Cepheids should be studied on a star-by-star basis.

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REFERENCES

- Anderson R. I. 2013, Classical Cepheids: High-precision Velocimetry, Cluster Membership, and the Effect of Rotation; PhD Thesis, University of Geneva
- Berdnikov L. N. 2008, VizieR On-line Data Catalog: II/285
- Berdnikov L. N., Dambis A. K., Vozyakova O. V. 2000, *A&AS*, 143, 211
- ESA 1997, The Hipparcos and Tycho Catalogues, ESA SP-1200
- Evans N. R. 1985, in Proc IAU Coll. 82, Cepheids: Theory and Observations, ed. B. F. Madore, Cambridge Univ. Press, p. 79
- Evans N. R. 1992, *ApJ*, 384, 220
- Freedman W. L., Madore B. F. 2010, *ARA&A*, 48, 673
- Irwin J. B. 1961, *ApJS*, 6, 253
- Luck R. E., Andrievsky S. M., Kovtyukh V. V., Gieren W., Graczyk D. 2011, *AJ*, 142, 51
- Luck R. E., Lambert D. L. 2011, *AJ*, 142, 136
- Madore B. F., Fernie J. D. 1980, *PASP*, 92, 315
- Miller J., Preston G. 1964a, *PASP*, 76, 47
- Miller J., Preston G. 1964b, *ApJ*, 139, 1126
- O’Connell D. J. K. 1951, *Publ. Riverview Coll. Obs.*, 2, 100
- Pel J. W. 1976, *A&AS*, 24, 413
- Pickering E. C. 1906, *Harvard Circ.*, No. 115, 1
- Pickering E. C. 1912, *Harvard Circ.*, No. 170, 6
- Pont F., Burki G., Mayor M. 1994, *A&A*, 105, 165
- Pojmanski G. 2002, *AcA*, 52, 397
- Sterken C. 2005, in Sterken C. ed., The Light-Time Effect in Astrophysics, ASP Conf. Ser. 335, Astron. Soc. Pac., San Francisco, p. 3
- Szabados L. 2003a, *Inf. Bull. Var. Stars*, 5394
- Szabados L. 2003b, in *Recent Res. Devel. Astron. & Astrophys.*, 1, 787

- Szeligowski S. 1926, Bull. Astr. Inst. Neth., 3, 177
Usenko I. A., Berdnikov L. N., Kravtsov V. V., Kniazev
A. Yu., Chini R., Hoffmeister V. H., Stahl O., Drass H.
2011, AstrL., 37, 718
Walraven Th., Muller A. B., Oosterhoff P. T. 1958, Bull.
Astr. Inst. Neth., 14, 81

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